Economic evaluation of materials handling systems in a deep open pit mine

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Abstract: Materials handling constitutes a large portion of the costs of mining operations. Therefore, the system chosen must be cost-effective yet meet the production demands of the mine. In this paper, unit haulage costs, economic risk and sensitivity analyses were conducted to determine the optimal way of handling materials in a deep open pit mine between the traditional truck-shovel haulage system (TSHS) and in-pit crushing and conveying (IPCC) haulage system. The results show that the IPCC haulage system has lower unit costs than the TSHS. The NPV of IPCC system is US\$ 15.09×10^9 while that of the TSHS is US\$ 14.64×10^9; the DPP of the TSHS and IPCC systems are 2.94 months and 2.13 months, respectively, while the IRR of the TSHS and IPCC systems are 147% and 185% respectively. As the NPVs of both systems are positive, with very short DPPs and high IRRs, the systems are considered to be economically viable. However, the IPCC is considered more economically viable than the TSHS. The NPV of IPCC is less sensitive to variations in the input variables compared to TSHS.

Keywords: truck-shovel haulage system; TSHS; in-pit crushing and conveying; IPCC; net present value; NPV; discounted payback period; DPP; internal rate of return; IRR.

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1 Introduction

Mining operations in hard rock conditions involve rock breakage, materials handling and processing or treatment. According to Alberts (1984) and Suglo (2010), materials handling constitutes up to 40% of the total open pit mining costs. Therefore, the method chosen for handling materials out of the open pit has to be cost-effective, environmentally friendly and yet meet the production demands of the mine. Dzakpata et al. (2016) argued that the traditional truck-shovel haulage system (TSHS) is used in 95% of open-pit mines worldwide due to its flexibility and economy of scale. TSHS is the only method used in surface mines in Botswana. This haulage system has a reasonable capital expenditure (CAPEX) but has a very high operating expenditure (OPEX). The system comprises of an excavator (shovel) loading the blasted materials into dump trucks in the pit, the trucks then haul the materials out of the pit through ramps and haul roads and dump it at the crusher, stockpile or dumpsite and return to the assigned excavator for another load. As the depth of the pit increases with time, the trucks take longer times to haul the materials out of the pit. The longer truck cycle times result in low production per given time and high fuel consumption. To achieve the targeted production, more trucks must be added to the fleet to handle the materials.

In-pit crushing and conveying (IPCC) haulage system is another option for handling materials out of pits. IPCC haulage systems have been advanced as offering a real alternative to TSHS for mines that have more than ten years life of mine (Nehring et al., 2018). The system consists of a combination of loading the materials using excavators and feeding it into an in-pit crusher, crushing, conveying, and discharging the materials out of the pit (Osanloo and Paricheh, 2019). Even though this system offers low OPEX, it has not been widely used in handling materials in open pits due to its high CAPEX requirements and the difficulty to move the conveyor belts in multiple bench operations to meet the advance in the different mining faces.

This paper analyses the operation and economics of TSHS and IPCC systems in a deep open pit mine to determine the cost-effective method of handling materials. Thus, a thorough evaluation of the production performance of the two haulage systems, their economic, social, safety, environmental and technical factors were conducted. The capital and operating costs are used to compare the two haulage systems using cost per tonne, net present value (NPV), discounted payback period (DPP) and internal rate of return (IRR). Risk and sensitivity analyses were also conducted to determine how changes in production rates, discount rates and cost per carat affect the NPV of the two systems.

2 Literature review

The literature review that was conducted in this study is presented in the following sections.

2.1 Truck shovel haulage system

TSHS constitutes 50–60% of the total operating cost in open pit mining (Ercelebi and Bascetin, 2009). Fuel costs alone constitute about 45% of the operating costs. The costs of fuel, labour, tires and parts increase with pit depth as longer haul distances result in a lot of diesel consumption by the dump trucks. Also, to meet production demands, more trucks have to be added to the fleet as the pit gets deeper which results in increased fuel consumption, higher maintenance costs and personnel requirements.

2.2 In-pit crushing and conveying haulage system

The IPCC system is either a continuous or semi-continuous materials handling system that allows ore to be crushed within the pit and hauled out of the pit using conveyor belt systems. As in the TSHS, excavators (rope and hydraulic shovels), which are either diesel or electricity operated, are used to feed the crusher with the broken materials (Kennedy, 1990). According to Mohammadi et al. (2011), the crushing systems can either be fully mobile, semi-mobile or fixed. Fixed and semi-mobile crusher systems use shovels coupled with dump trucks as their feeding systems while fully mobile crushing systems are fed directly by shovels. The conveyor belt system transports materials out of the pit and it is coupled with spreaders (for waste) or stackers (for ore) at the end as part of the discharge system.

Jeric and Hrebar (1997) list the benefits of IPCC over TSHS for large open-pit mines as continuous haulage of materials, increased mine and road safety due to fewer moving vehicles on the haul roads, reduced road maintenance requirements, reduced dust generation, lower labour requirements, lower utility costs if electrical power is used instead of diesel, reduced emission of greenhouse gases and noise generation. According to Dean et al. (2015), the disadvantages of IPCC compared to TSHS include a significant up front CAPEX because the crusher and full length of the belt conveyor have to be bought and installed at the start of production, whereas trucks can be bought in stages during the life of the mine production, the system reduces the ability of a mine to switch mining to a different zone to adapt to unforeseen changes in market conditions, ore grade or geology. Also, since the system comprises a series of connected units, a shutdown in any component of the system affects the entire production from the pit.

2.3 Economic evaluation criteria

The huge capital involved in mining projects make them high risk ventures. Therefore, it is necessary to conduct economic analysis on existing and new projects to determine the acceptability or attractiveness of the projects and decide on the best project to invest in (Suglo, 2010). According to Ocneanu and Cristian (2014), economic analysis is the procedure for assessing the opportunity of a project by considering the benefits compared to the costs in monetary terms. Different economic evaluation criteria such as net present value (NPV), internal rate of return (IRR), payback period (PP) and discounted payback period (DPP) are usually used individually or in combination to help in the economic evaluation of projects for selection. While payback period gives the time required to recover the initial investment in a project from operations (Hayes, 2020), NPV is a predictor of the reliability of future cash flows from an investment opportunity by discounting the difference between the present value of cost inflows and the present value of cash outflows taking interest and inflation rates into account (Ong and Chun, 2013). The discounted payback period gives the number of years it takes to break even from undertaking the initial expenditure by discounting future cash flows and recognising the time value of money. The IRR is the discount rate at which the present value of estimated cash flows is equal to the initial investment (Christodoulou, 1996).

2.4 Sensitivity and risk analysis

Anon. (2013) notes that sensitivity and risk analyses help engineers and investors to identify the critical factors that are subject to risks in a project, the source of risks, the probable variation of the risk factors and lead to improved project design, and the determination of actions to mitigate the major sources of the uncertainties. Risk analysis is used to estimate the probability distribution of project outcomes and helps to minimise future negative unforeseen outcomes. According to Jovanovicâ (1999), sensitivity analysis is a procedure that analyses how changes in certain input values influence certain output criteria values (e.g., the IRR and NPV) and the evaluation of the total investment in the project.

3 Data analysis

Data was gathered from previous mining reports over a period of five years at Jwaneng Mine which is a deep open pit mine in Botswana for TSHS. For the IPCC system, data was obtained from the internet, journals and reports from mining companies which have either used or are currently using the system. The data was then used to calculate the unit haulage costs, to conduct economic, sensitivity and risk analyses on the two materials handling options.

4 Case study

The open pit diamond mine used for this analysis is currently using TSHS for handling the ore and waste. Currently, the mine has 3 active mining phases, which are Cuts 7 to 9 (see Figure 1). Waste is mined from all three phases, while ore is only mined from Cuts 7 and 8. The daily production targets are 34,000 tonnes of ore and 90,000 tonnes of waste from benches which are 16 m high, 8 m wide and bench slope angles of 85o. The mine has scheduled 357 working days per year with three 8-hour long shifts per day. The surface crusher is located about 1,436 m from the pit, while the waste dumps are located about 3,306 m from the pit. The mine uses Komatsu 930E rear dump trucks with a capacity of 300 tonnes to haul both ore and waste out of the pit. The Komatsu 930E dump trucks have 80,000 hours of expected operating life, 80% availability and 85% utilisation.

For IPCC, conveyor belts and spreaders of 1,500 tph capacity were selected to meet the mine’s daily ore production target. In-pit conveyors of 1,200 mm and overland conveyors of 1,000 mm width were chosen with belt speeds of 1.57 m/s and 2.26 m/s, respectively. In evaluating the IPCC system, the ore was to be hauled by conveyor belts while waste would be hauled by the traditional TSHS.

Figure 1 Satellite map of the open pit mine (see online version for colours)

Source: Anon (2021)

The kimberlite pipes of the mine are about 100 m below the surface, with the centre pipe and north pipe fully exposed by the extraction of Cuts seven and eight. At the end of the extraction of Cuts seven and eight, the final pit dimensions will be 2 km × 600 m with an overall pit slope angle of 42° and it will be 624 m below the surface. The analysis in this study started from 112 m below the surface at Bench eight downwards and include benches that contained both ore and waste.

4.1 Unit haulage cost calculations

The production parameters and capacities of the equipment in each system were used to determine the unit cost per tonne of the two materials handling systems in this study. The cost per hour for each haulage system includes the ownership and operation costs of the equipment used. Ownership costs include purchase costs, delivery costs, tax, insurance and interest while operating costs include replacement costs, repair and maintenance costs, fuel and electricity costs, lubrication costs and labour costs.

4.1.1 Unit haulage cost of TSHS

Cycle times of dump trucks in each bench were determined and used to determine the number of dump trucks required per day on each bench. This was then used to calculate the haulage costs on each bench per hour of the TSHS using the mine's estimated haulage costs of the Komatsu 930E trucks as US$ 696.82 per hour. The calculated haulage costs per hour were converted to haulage costs per tonne using equation 1 and the results are presented in Table 1.

$$Unit\ Cost\,(US\$/t),\,U_c = \frac{U_{hr}}{T_c \times \dfrac{60}{C_t}} \tag{1}$$

where: U_{hr} unit cost per hour (US$/hr); T_c = truck capacity (tonne)

C_t cycle time of truck (min)

From Table 1, the number of dump trucks required per day on each bench and the unit haulage costs per bench increase with pit depth for both waste and ore haulage. However, the unit costs of waste are higher on each bench for waste than for ore due to the much longer haul distances to the waste dumps. It is also noted that the total unit haulage cost of the TSHS increased as the depth of the pit increased from US$ 32/tonne on bench #8 to US$ 97/tonne at bench #40. It can also be observed from Table 1 that while some benches (e.g., Bench Nos. 8 to 15) require the same number of dump trucks to mine ore, their unit haulage costs are different due to the different haul distances.

Table 1 Unit cost of TSHS

Bench no.	*Ore trucks required/day*	*Unit cost ore (US$/tonne)*	*Waste trucks required/day*	*Unit cost waste (US$/tonne)*	*Total TSHS unit cost (US$/tonne)*
8	4	6	13	26	32
12	4	6	14	31	37
15	4	7	15	35	42
16	5	9	15	36	45
19	5	10	16	40	50
22	5	10	17	45	55
25	6	13	17	47	60
26	6	13	18	51	64
29	6	14	19	57	71
32	6	15	20	62	77
34	7	18	20	64	82
36	7	19	21	70	89
39	7	20	22	76	96
40	7	20	22	77	97

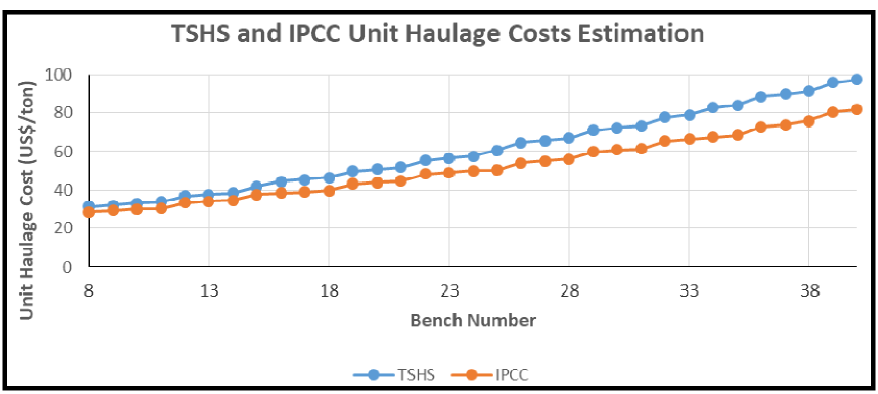
4.1.2 Unit haulage cost of IPCC

Komatsu 930E dump trucks were used together with in-pit conveyors and overland conveyors to haul ore to the processing plant while waste was hauled by dump trucks. Therefore, the overall unit haulage cost of this system will be the unit cost of waste haulage by dump trucks, the dump trucks that feed the ore into semi-mobile crushers within the pit, in-pit conveyors, overland conveyors, and spreaders. It was assumed that the daily production of the IPCC system is the same as that of TSHS. So, the unit cost per tonne per bench for waste will be the same as that of waste in TSHS. The calculations were done based on moving the in-pit crusher every five years. The in-pit crusher will be moved 6 times during the life of the mine. It will initially be stationed at Bench #7 and then moved to Bench Nos. 10, 13, 16, 19, 24 and 30 with time. The results of the calculations are summarised in Table 2.

Table 2 Unit haulage cost for IPCC

Bench no.	*Ore trucks needed/day*	*Unit cost of ore dump trucks (US$/tonne)*	*Unit cost of conveyors (US$/tonne)*	*Ore unit cost (US$/tonne)*	*Waste unit cost (US$/tonne)*	*Total unit cost (US$/tonne)*
8	2	1.21	1.52	2.73	25.87	28.60
9	2	1.31	1.52	2.83	26.48	29.31
10	2	1.40	1.52	2.92	27.10	30.02
11	2	1.20	1.57	2.77	27.71	30.48
13	2	1.39	1.57	2.96	31.16	34.12
14	2	1.18	1.61	2.79	31.82	34.61
17	2	1.16	1.65	2.81	36.22	39.03
20	2	1.15	1.69	2.84	40.90	43.74
25	2	1.12	1.74	2.86	47.47	50.33
30	2	1.59	1.74	3.33	57.54	60.87
31	2	1.09	1.78	2.87	58.44	61.31
32	2	1.18	1.78	2.96	62.45	65.41
37	2	1.65	1.78	3.43	70.54	73.97
38	3	2.62	1.78	4.40	71.53	75.93
40	3	2.90	1.78	4.68	77.01	81.69

Figure 2 Estimated unit haulage costs of TSHS and IPCC at cuts seven and eight (see online version for colours)



From Table 2, the number of in-pit dump trucks required per day will be the same from Bench #8 to Bench #37. At Bench #38, an additional dump truck will be required to meet the daily production target for waste due to longer cycle times that result from traveling over longer haulage distances. The changes in cycle times are reflected in the unit haulage costs, which fluctuate as mining progresses due to the relocation of the in-pit crusher. The relocation of the crusher also affects the length of the in-pit conveyor and consequently the unit haulage cost. Table 2 also shows that the length of the in-pit conveyor is constant for the years that the crusher is stationery and changes only when the crusher is relocated. This is reflected in the unit haulage cost of conveyors over the years. The total unit haulage cost of the IPCC increases as the depth of the pit increases from US$ 28.60/tonne on Bench #8 to US$ 81.69/tonne at Bench #40.

From Figure 2, the IPCC has lower unit haulage costs than the TSHS especially as the pit deepens from Bench #8 to Bench #40. At the beginning of the operations at Bench #8, the unit haulage costs of both options are almost the same (with a difference of US$ 3.4/tonne), but as mining progresses, the difference in unit haulage costs between the TSHS and IPCC increase to US$ 15.3/tonne at Bench #40.

4.2 Economic evaluation

The net present value (NPV), discounted payback period (DPP) and internal rate of return (IRR) were used to compare the economic viability of the two materials handling systems. The results are summarised in Table 3.

Table 3 Economic parameters for TSHS and IPCC comparison

Economic parameter	*Haulage System*	
	TSHS	*IPCC*
NPV (US$ $\times 10^9$)	14.64	15.09
DPP (months)	2.94	2.13
IRR (%)	147	185

Note: Exchange rate: US$ 1.00 = BWP 11.58, BWP = Botswana Pula

From Table 3, both systems have positive NPVs which shows that both projects are viable, but the IPCC has higher NPV than TSHS. Thus, the IPCC system is considered more favourable than the TSHS. The results also show that the DPPs of the TSHS and IPCC are very short i.e., 2.94 months and 2.13 months respectively. This indicates that both systems are viable. However, IPCC is considered more economically attractive than TSHS due to its shorter DPP. The IRR for the TSHS is 147% while that of IPCC in ore and waste is 185%. These are higher than the company's hurdle rate of 15% and show that both systems are economically feasible for use in materials handling.

4.3 Risk analysis

To characterise the risks involved in investing in the TSHS and IPCC systems, risk analysis was done by conducting a probabilistic simulation on the NPV of each option using Monte Carlo Simulation with the @RISK software. Fig. 3 shows the results of the simulation. From Figure 3, there is 21.3% probability that the NPV for ore and waste haulage using TSHS will be negative while that of IPCC system is 19.2%. Table 4 summarises the maximum, minimum and average net present values of the TSHS and IPCC systems as well as the feasibilities of the two options at various discount rates using Monte Carlo simulation.

Figure 3 Probability density of NPV for TSHS and IPCC haulage systems

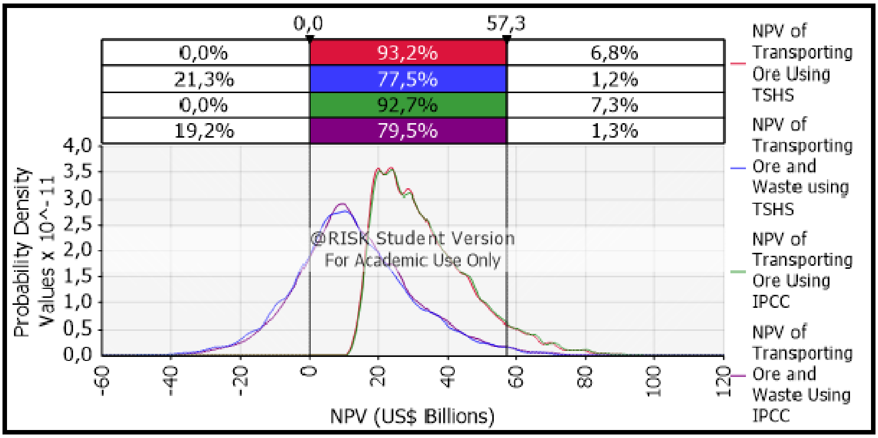


Table 4 NPV of TSHS and IPCC haulage systems

	TSHS		*IPCC*	
	NPV of ore (US$ × 10⁹)	*NPV of ore and waste (US$ × 10⁹)*	*NPV of ore (US$ × 10⁹)*	*NPV of ore and waste (US$ × 10⁹)*
Minimum (12%)	9.87	–50.87	10.07	–544.70
Maximum	105.79	86.40	107.09	–47.12
Mean	33.48	12.53	33.95	87.11
Std Dev	13.77	17.07	13.96	13.53
20%	18.49	–7.76	18.76	16.81
50%	30.55	11.29	30.98	–6.33
70%	38.64	19.75	39.18	12.11
80%	44.41	26.15	45.05	20.56
90%	52.46	34.76	53.21	26.99
99%	74.62	57.15	75.60	35.55

Note: Exchange rate: US$ 1.00 = BWP 11.58, BWP = Botswana Pula.

From Table 4. the minimum NPV for ore handling alone over the life of mine is US$ 9.87 × 10^9 for the TSHS while that of the IPCC system is US$ 10.07 × 10^9. Both NPVs are positive which shows that both projects will be viable even in the worst-case scenarios of the input variables. However. the IPCC system is better than the TSHS in the worst-case scenario due to its higher NPV than TSHS. It can also be observed from Table 4 that both projects will not be viable when the discount rate is 12% when handling both ore and waste as the values of the NPVs are negative. Table 4 also shows that at the mean and maximum discount rates the IPCC has higher NPVs than TSHS option.

4.4 Sensitivity analysis

A sensitivity analysis was conducted using @RISK software on both systems. Spider graphs were plotted to show the percentage change in the input values against the change in the output from the base output value. Figure 4 and Figure 5 are spider graphs of NPV of the TSHS and IPCC systems respectively against ore production, price of the diamonds (US$/carat), grade of the ore in (carats/ton), discount rate and the initial cost of the dump trucks. Both graphs show that the NPVs are highly affected by variations in ore production rate, moderately affected by the price of diamonds and ore grade, and inversely affected by the discount rate. This is because the ore production rate has the steepest gradients in both graphs.

From Figure 4, a 5% change in ore production will give a NPV of US$ 17.61×10^9 while a 95% change in ore production will give an NPV of US$ 61.54×10^9 for the TSHS. However, Figure 5 shows that a 5% change in ore production will result in a NPV of US$ 17.38×10^9 while a 95% change in ore production will give an NPV of US$ 60.72×10^9 for IPCC system.

Figure 4 Spider graph of NPV of ore haulage using TSHS (see online version for colours)

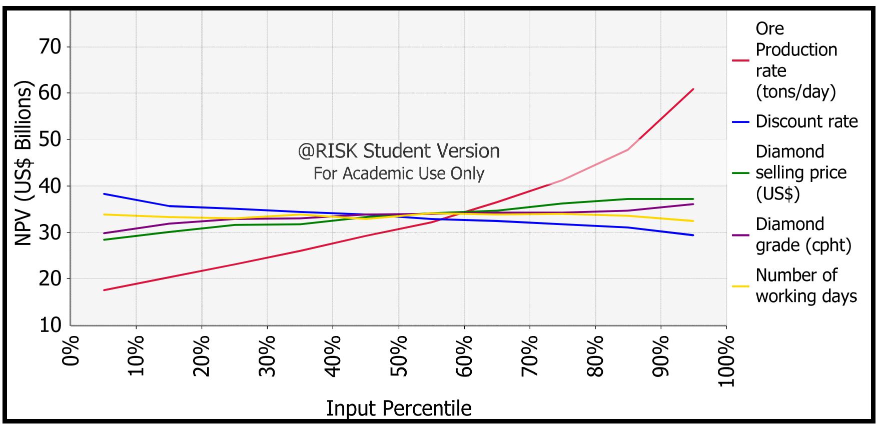
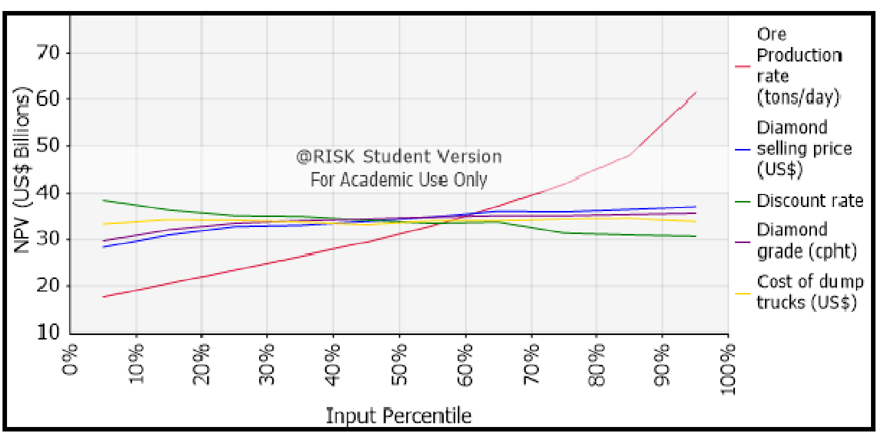


Figure 5 Spider graph of NPV of ore haulage using IPCC haulage system (see online version for colours)



5 Conclusions

In this paper, economic evaluation, risk and sensitivity analyses were conducted on a deep open pit diamond mine to determine the optimal materials handling system. The results show that the unit haulage costs of the IPCC option do not increase as much as TSHS as the pit deepens. The unit haulage cost of IPCC increased by 42% from the beginning of production at Bench #8 to the end of production at Bench #40 while that of TSHS option increased by 72%. The economic evaluation shows that IPCC is more economical than TSHS as all the economic parameters evaluated (e.g., NPV, IRR and DPP) gave better results for IPCC than TSHS. The NPV of IPCC system was calculated to be US\$ 15.09×10^9 while that of the TSHS was US\$ 14.64×10^9, the DPP of the TSHS and IPCC systems were 2.94 months and 2.13 months respectively, while the IRR of the TSHS and IPCC systems were 147% and 185% respectively.

The risk analysis conducted on the two options shows that there is 21.3% probability that the NPV of TSHS will be negative while that of IPCC system is 19.2%. The results of the sensitivity analysis show that the NPVs of the two options are highly affected by changes in ore production rate, moderately affected by the price of diamonds and ore grade but inversely affected by the discount rate. It is noteworthy that the impact of variations in these input variables on the NPV are higher in the TSHS option than for IPCC system. For example, a 5% change in ore production costs results in the NPV of TSHS which is US\$ 0.23×10^9 higher than that of IPCC and a 95% change in ore production rate results in the NPV of TSHS being US\$ 0.82×10^9 higher than IPCC. This shows that IPCC haulage system is a potentially more economical materials handling system than TSHS.

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